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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

Variable Speed Transmissions

Thin Oil Film Lubrication

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THE TEXAS COMPANY
TEXACO PETROLEUM PRODUCTS

THE POWER FACTOR IN THE VARIABLE SPEED TRANSMISSION

SPEED change has been a vital factor in the development of practically every industry wherein the transmission of power is involved. The evolution of mechanical means of production required speeds of varying intensity: speeds commensurate with the productive ability of the machinery employed; speeds so readily controllable as to promote the maximum of economy from the viewpoint of power consumption.

There is a direct tie-up between speed and power. But of more pertinent interest is the relation between speed, power and friction, for power consumption and speeds developed are directly dependent upon the extent to which friction is maintained at a minimum. It is for this reason that the builders of power transmission and speed reduction equipment have studied the problem of lubrication from the angle of the scientist, and have developed their various lubricating systems to meet the requirements of practical engineering.

The evidence of these accomplishments is portrayed by the various illustrations which accompany the following article on the "Lubrication of Variable Speed Transmissions." The proof of their practicability is borne out by the power bill in the average plant where they are installed. In effect, it is just another instance of good judgment in machine design coupled with an appreciation of the importance of effective lubrication.

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LUBRICATION

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Variable Speed Transmissions

Lubrication of the Mechanical Type

FLEXIBILITY in speed control is a most important factor in power transmission. In realization of this, there has been a decided trend towards the development of the variable speed transmission for the purpose of improving power transmission economies in the operation of a wide variety of industrial machinery. The variable speed transmission enables speed control to a most accurate degree; it has eliminated the limitations of fixed speed reductions, and by its adaptability to centralized lubrication it has become a highly dependable and yet sensitive mechanism. The manner in which lubrication has been studied in connection with the design of such devices is of distinct interest.

Speed control can be attained by oil hydraulic power or by electro-mechanical means involving gears or belt connections and cone or V-shaped pulleys. Oil hydraulic systems were discussed in considerable detail in LUBRICATION, April, 1934. The lubrication requirements of the mechanical type of transmission will be of equal interest.

The mechanical type of variable speed transmission can be broadly divided into two groups, according to the manner in which speed control is brought about. In the geared motor installation there is a definite set of selective gear ratios which can be readily changed to afford a corresponding set of speeds at the driving end. The belt and V-type pulley transmission, in turn, provides for a more flexible variation in the speed of the driven member by change of the angle between the sides of the pulleys. This change in angle brings about a corresponding change in the operating diameters of the driving and driven pulleys.

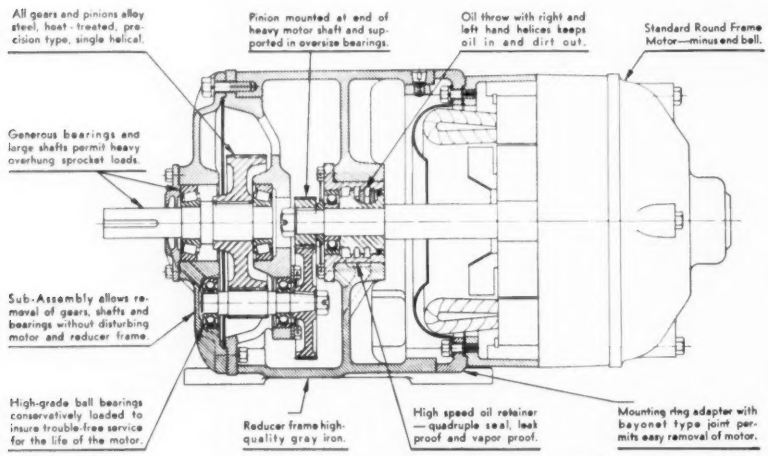
Both of the above types of transmission are distinctive for their low cost and their silent, efficient operation.

GEARED MOTORS

The geared motor has gained considerable popularity as a replacement unit in service where a limited range of selective speed changes is applicable and where floor space and first cost is a factor. Where direct current is available it is, of course, practicable to bring about speed change in the motor itself by suitable control of the fields, or, in other words, by change in resistance. With alternating current, however, mechanical means for speed change must be provided. The geared motor has lent itself admirably to such service. In particular it has enabled the use of higher speed motor design which is less costly than slow speed types of motors. In average service a speed range at the driven end of from ap-

proximately one-ninth to three times the speed of the motor armature is available.

Speed change within the unit itself is attained by means of gearing meshing with a pinion mounted directly on the armature shaft or connected thereto by a flexible coupling.


All gears and pinions alloy steel, heat-treated, precision type, single helical.
Pinion mounted at end of heavy motor shaft and supported in oversize bearings.
Oil throw with right and left hand helices keeps oil in and dirt out.
Standard Round Frame Motor—minus end bell.
Generous bearings and large shafts permit heavy overhung sprocket loads.
Sub-Assembly allows removal of gears, shafts and bearings without disturbing motor and reducer frame.
High-grade ball bearings conservatively loaded to insure trouble-free service for the life of the motor.
Reducer frame high-quality gray iron.
High speed oil retainer — quadruple seal, leak proof and vapor proof.
Mounting ring adapter with bayonet type joint permits easy removal of motor.

Courtesy of The Falk Corporation

Fig. 1—Showing the Falk integral type Motoreducer. Note the adaptability of the ball and roller bearing to the gear and pinion shafts, and also to the main shaft of the driving motor. By virtue of design of this unit, lubrication of both bearings and gears can be positively maintained with minimum possibility of leakage of oil or entry of contaminating foreign matter.

Lubrication Depends on Design and Operation

Where operation is practicable within the available range of speeds of the geared motor, there is present a most convincing argument in its favor by virtue of the protection afforded lubrication. The possibility of leakage of lubricants and, by the same premise, entry of contaminating foreign matter is virtually eliminated in this device. It is therefore but necessary to be assured that the lubricant or lubricants used are best suited to the design and operating conditions. From this point on only periodic inspection will be necessary, with flushing and renewal of lubricant should operation have imposed a severe load. The frequency of this latter should be decided upon in accordance with the builder's recommendations and the ability of the lubricants to stand up under the operating conditions.

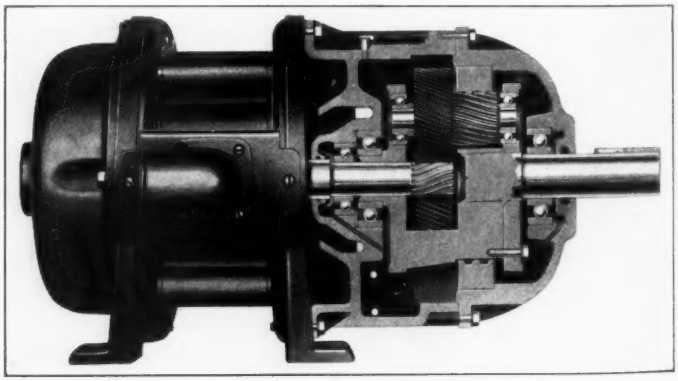
Bearing Design

Ball and roller bearings have been widely adapted to geared motor installations. In some they are lubricated independently from the gear set; in others the one lubricant serves all inboard moving parts. Where sealed type ball bearings are used a highly refined specially compounded grease of medium consistency will be suitable. It is very essential that such a lubricant be resistant to oxidation and breakdown, otherwise gum formation within the bearing elements may develop to increase the power consumption materially and perhaps ultimately to cause bearing failure if actual sticking of the balls or races occurs.

Gear Lubrication

The reduction gear set, however, is designed for oil lubrication, the oil being carried in the base of the gear case at a sufficient level to permit proper dipping of the lower gear, according to the accepted principles of bath lubrication. Experience has indicated that by reason of the comparatively fluid nature of the oil used, the lower gear should be about half submerged. In the average unit, this will mean that the gear case should be from one-third to one-half full of oil.

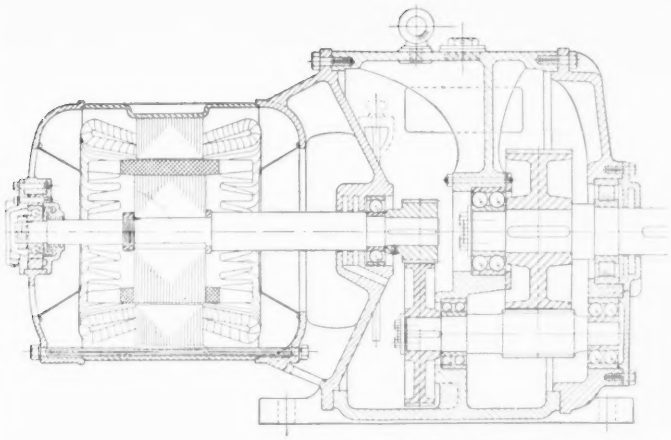
The viscosity of this oil should normally range from 500 to 900 seconds Saybolt at 100 degrees Fahr. In actual practice one must, of course, decide on the most suitable viscosity only after careful consideration of the prevailing motor temperatures and the extent to which heat will be transmitted to the gear case or



Courtesy of General Electric Company

Fig. 2—Showing cutaway view of a General Electric geared motor. The oil used in the gear housing should have the viscosity of a medium heavy motor oil. It is interesting to note the relative location of the gears to the driving elements and here again the adaptability of the ball bearing to this type of installation.

developed therein. There will always be a certain amount of temperature increase in any such installation. Radiation, however, will play an important part in preventing abnormal



Courtesy of Foote Bros. Gear & Machine Co.

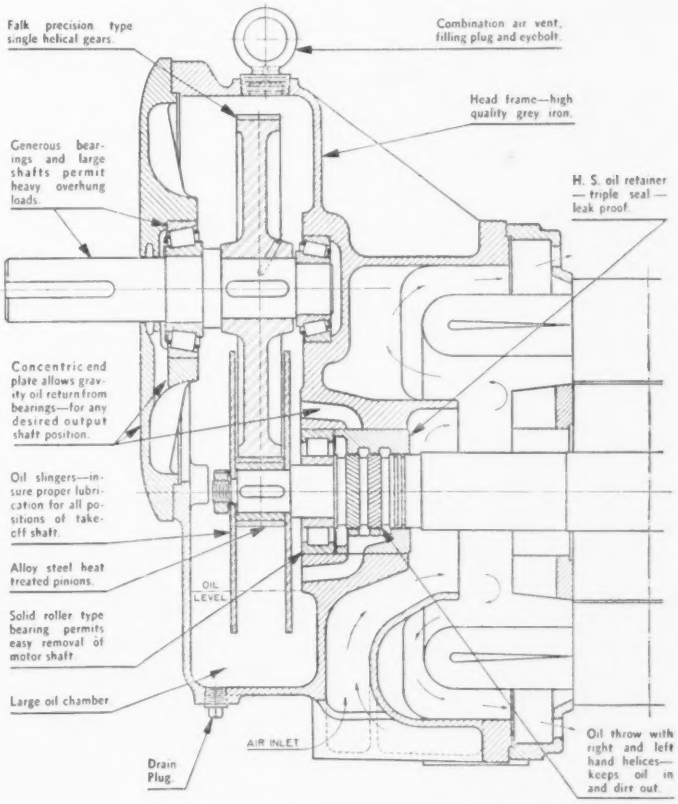
Fig. 3—Showing the Foote double-reduction motorized unit with provision for splash lubrication. The gears dip into the oil supply in the base of the machine and create sufficient agitation to force the oil to all parts of the unit. Bearings are provided with oil seals and oil returns to carry oil back to the base.

increase in gear case temperatures, according to the location. Where transmitted and induced temperatures are not severe, obviously an oil of lower viscosity will develop less drag and internal power consumption. This is an important factor in calculating the ultimate efficiency of any such installation.

V-BELT AND FLEXIBLE CHAIN TRANSMISSIONS

The variable speed transmission of the V-Belt or flexible chain type is built either open or enclosed, according to the prospective service and the importance of first cost. Open type installations are practicable where surroundings are comparatively clean. They can, furthermore, be readily adapted to limited space by mounting the motor on a platform above the transmission. Alignment and belt take-up in such a job can be made by changing the location of the motor with respect to its base.

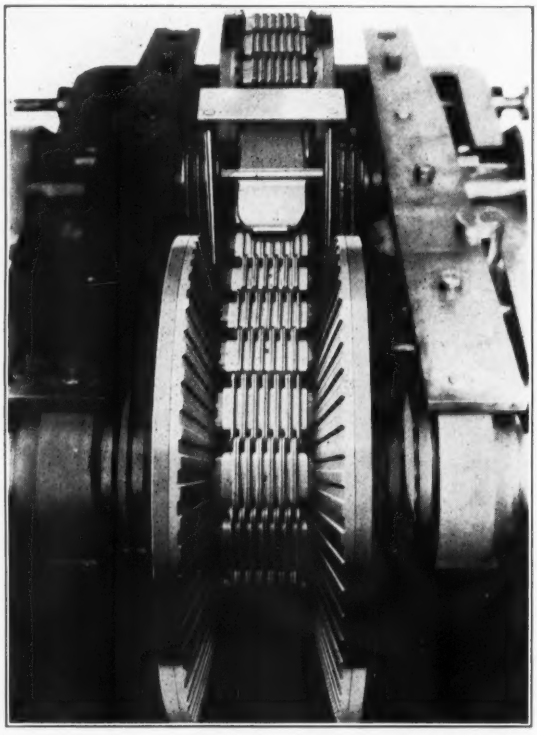
Enclosed type transmissions, wherever the motor forms an integral part of the transmission, provide for location of the motor and unit together in a suitable housing which effectively reduces lubrication troubles, by preventing the entry of foreign matter. Power is transmitted by a flexible chain or V-shaped belt which forms the connection between the adjustable pulleys. Side contact prevails between these elements in contrast to the more conventional type of chain or belt drive installation wherein power is transmitted through face contact of the chain or belt with the sprockets or pulleys. The adjustable pulleys are built up from a set of opposed conical discs. Speed of the connecting chain or belt is varied by changing the distance between these discs or, in other words, by changing the effective radius of the arc over which the chain or belt is moving. Such changes can be made under load without steps and so gradually that jerky motion is entirely eliminated. Separation of one pair of discs simultaneously brings together the opposite pair. As a result, even though the speed of the driving shaft may always be practically as constant as the speed of its driving motor, for example, the speed of the driven shaft can be increased or decreased by altering the effective or driving diameters over which the connecting belt or chain is operating.


Falk precision type single helical gears.
Combination air vent, filling plug and eyebolt.
Head frame—high quality grey iron.
Generous bearings and large shafts permit heavy overhung loads.
H. S. oil retainer — triple seal — leak proof.
Concentric end plate allows gravity oil return from bearings—for any desired output shaft position.
Oil slingers—insure proper lubrication for all positions of take-off shaft.
Alloy steel heat treated pinions.
OIL LEVEL
Solid roller type bearing permits easy removal of motor shaft.
Large oil chamber.
AIR INLET
Drain Plug.
Oil throw with right and left hand helices—keeps oil in and dirt out.

Courtesy of The Falk Corporation

Fig. 4—Showing details of the Falk geared-head Motoreducer. Note that provision is made for oil lubrication of both gears and bearings. By use of suitable oil retainers, entry of dirt or leakage of lubricant at the motor end is prevented.

In the V-belt type of drive where smooth surface discs are employed, it is normally advisable to make speed changes or adjustment while the unit is in operation, in order to permit the belt to adjust itself to the surfaces of the discs. In general, whatever the design, such changes are made by hand, by means of a suitable hand wheel located either on the transmission itself, or through a suitable crank and roller chain connection for remote control where the unit is installed beyond reach. Provision for electric remote control has also developed for such service or for operation of two or more transmissions off the same control unit.



Courtesy of Link-Belt Company

Fig. 5—Top view of the Link-Belt P.I.V. gear, showing toothed design of the wheels and tooth formation of the chain on the minimum diameter of a wheel. The chain used in this type of gear is made up of a series of overlapping steel leaves. The assembly of these leaves takes the place of teeth on the inner surface of the chain. Note that the teeth of the discs or wheels widen from the center outward toward the circumference, being of uniform depth. This entire mechanism is designed to run in an oil bath which is retained by a compact cast-iron housing.

Lubrication

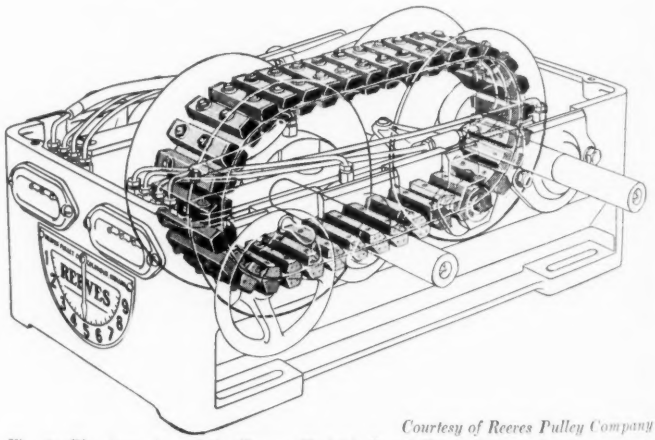
The types of lubricants which should be used in any such transmission will depend upon the design, the pulley or disc construction and the nature of the connecting chain or belt.

Where belts of fabricated rubber, leather or textile materials are used, lubrication is confined solely to the bearings which support the pulley shafts, and take up the thrust developed by the lateral pressure of the belts against the discs which compose the pulleys. There is no necessity for lubricant in the transmission case; in fact, the presence of lubricant on the face of the pulley discs is decidedly objectionable. For this reason, bearing construction in the interest of preventing leakage has been carefully studied, resulting in the wide-spread adoption of the seal-type ball bearing.

Transmissions involving a flexible steel chain, however, require lubrication of the chain elements as well as the disc surfaces with which the chain is in contact. In such installations, a problem of chain as well as bearing lubrication is encountered. The problem is readily solved by use of a highly refined straight mineral oil. This lubricant also serves the ball bearings within the housing, which carry the wheel shafts and absorb radial and thrust loads.

Flexible Chain Requirements

Bearings in this type of an installation require less individual attention than the ball bearings in the V-belt transmission designed for grease lubrication by pressure gun. The same care must be observed, however, in regard to periodic flushing, to insure against accumulation of non-lubricating foreign matter. The primary purpose, of course, is to insure continuous and unimpaired rolling motion; this can be more successfully accomplished when the rolling elements are in proper alignment, with the minimum of deflection under load. Lubrication is a distinct aid in this regard.



Courtesy of Reeves Pulley Company

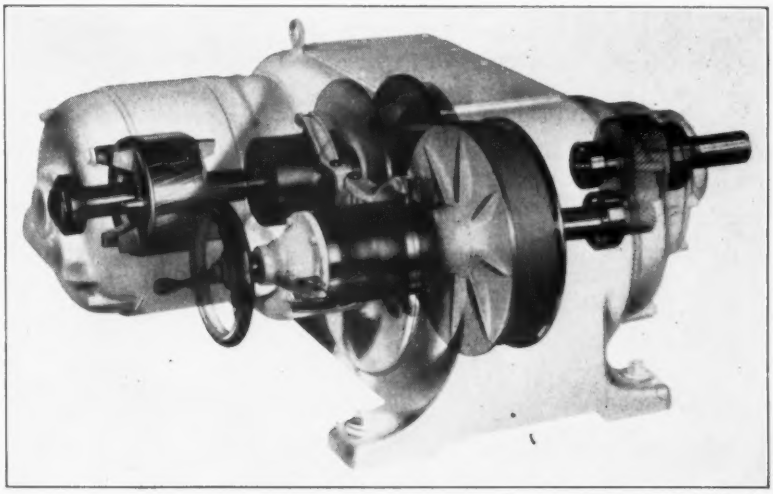
Fig. 6—Phantom view of the Reeves Variable Speed Transmission, showing manner of construction of the endless V-belt and its relative position with respect to the pulleys or wheels. It is interesting to note that these belts are made from fabricated cord belting sealed in rubber. They are, therefore, capable of absorbing considerable shocks.

Lubrication of a ball or roller bearing must also be studied with respect to speed and temperature. Both may vary widely in power

transmission service. Low temperatures may lead to decidedly sluggish action in certain types of lubricants, with consequent increase in power consumption. In service where a comparatively fluid lubricant must serve both bearings and the parts which compose a flexible steel chain, it is obvious that abnormal drag within the lubricant itself may seriously affect the power transmitting ability of the entire unit. The pour test of the lubricant, therefore, may frequently require careful consideration, along with the viscosity.

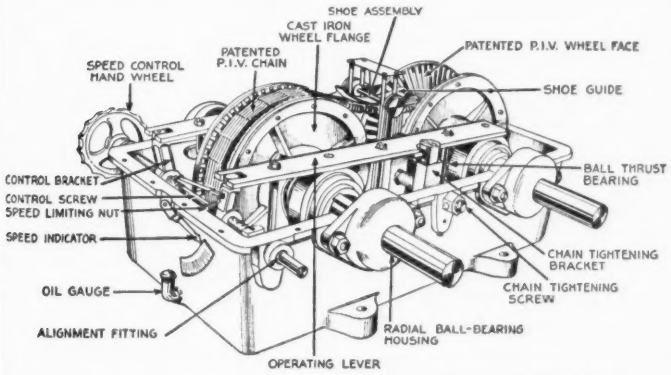
There is usually necessity for considerably higher viscosity in an oil for chain lubrication than will be required for a ball bearing under the same temperature conditions. In the latter, as speeds are increased, it is practicable to lubricate with an oil of lower viscosity. Under extremely high speeds an oil as low as 100 seconds Saybolt at 100 degrees Fahr. has proved to be capable of giving adequate protection with a minimum of temperature increase. In the variable speed transmission fortunately speeds do not range above normal electric motor speed, or in other words, above 4000 r.p.m. For such service an oil as low in viscosity as mentioned above would be out of line, both for bearings and chains, the minimum being perhaps around 500 seconds Saybolt at 100 degrees Fahr. A heavier oil will give greater protection of the pins, bushings and links which compose the chain, by its ability to resist the shock which is developed by engagement of the links with the teeth, which are built up on the surface of the discs which compose the pulleys. Obviously the frequency of such shocks will depend upon the speed of the unit.

The extent to which shock of this nature will be detrimental to lubrication will depend upon the load and constancy of operation. Rapid repetition upon the contact surfaces of the chains may prevent too light an oil from remaining between the chain leaves, pins and bushings, to result in wear and noisy operation. On the other hand, viscosity cannot be increased at will, inasmuch as the penetrative ability will vary directly with the viscosity or relative fluidity of the oil.



Courtesy of U. S. Electrical Mfg. Co.

Fig. 7—A phantom view of a U. S. Varidrive Synchrogear motor, showing details of the varibelt installation. All ball bearings are provided for grease lubrication.

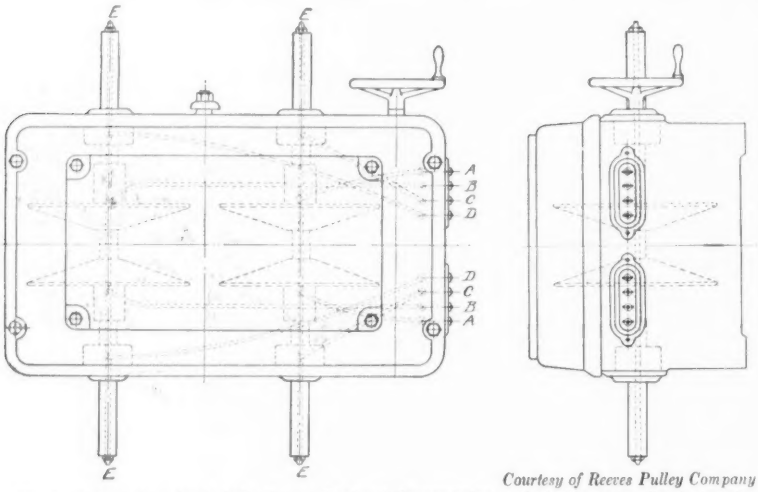


Courtesy of Link-Belt Company

Fig. 8—Angle view of the Link-Belt P.I.V. Gear, giving complete details of design and showing location of essential ball bearings and provision for lubrication.

The chief cause of wear in the flexible steel chain is bending or articulation, just as in the more conventional type of chain drive. Wear may occur on the parts which compose the chain and which move with respect to each other, or it may develop at the points of contact between the chain and its companion pulleys. Splash lubrication has been widely adapted to overcome this possibility. It has proved to be ideally adaptable to the oil-tight nature of the housing and the normal viscosity of oil which must be used to protect both the chains and bearings. In service, the entire mechanism functions in a veritable fog of oil and is thoroughly protected against entry of abrasive foreign matter. When a highly refined straight mineral oil is used, which is of sufficient body to maintain a pressure-resisting film and yet so fluid as to pene-

trate readily through the chain and bearing parts, there should be no difficulty from a lubricating viewpoint. In continued service, however, or when the transmission is operating under moisture, chemical or dust conditions, periodic cleaning is advisable, in keeping with recommended practice of the builders.



Courtesy of Reeves Pulley Company

Fig. 9—Lubrication chart of the Reeves Enclosed Transmission. (A) indicates two lubricators for the thrust bearing nearest to the shifting screw. (B) shows two lubricators for the thrust bearing farthest from the shifting screw. (C) shows two lubricators for the frame bearing nearest the shifting screw. (D) shows two lubricators for the frame bearing farthest from this latter. (E) indicates four lubricators for the disc hub; both discs on the same shaft may be lubricated from either end if necessary. This installation requires lubrication with a high grade low torque grease.

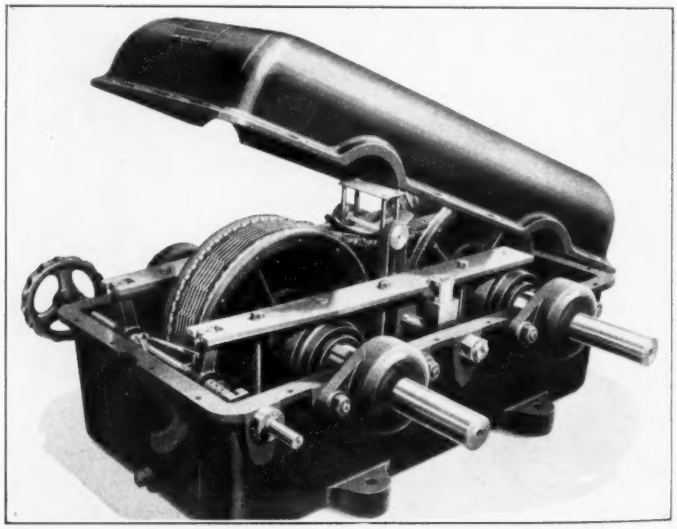
Grease Lubricated Ball Bearings

Ball bearings used in connection with V-belt transmissions are provided with means for pressure grease lubrication. Their construction also includes suitable sealing media to prevent leakage of grease and the possibility of contact with the power transmitting surfaces of the belts. Grease, in itself, is also an effective sealing medium provided it is of a comparatively heavy body. In a device such as the variable speed transmission, however, it is best to rely on mechanical means of sealing the bearings, for heavy greases are prone to lead to abnormal power consumption. For this reason, a grease of low torque characteristics and medium consistency, which is capable of functioning under comparatively high temperatures, has been regarded as best suited to the service involved.

Pressure Gun Operation

A most important item in the maintenance of grease-lubricated ball bearings concerns the method of application, especially when relubrication is necessary. The builders of variable speed power transmission units have largely adopted the pressure grease gun for ball bearing lubrication, suitable fittings for attachment of same being located on the bearing housing or connected thereto. This method of pressure lubrication is accepted as being highly efficient in protecting bearings capable of retaining a grease charge without leakage. Unfortunately, however, entirely too much grease can be forced into the bearing housing if the pressure gun is not carefully handled.

It is evident that this may readily lead to overheating, especially if the grease is too heavy. Such overheating is brought about by excessive internal friction within the lubricant itself. With certain types of grease, abnormal increase in temperature may cause sufficient decrease in body to result in separation of the oil from the soap, thereby causing marked reduction in lubricating value and loss of oil by leakage if the bearing is not oil-sealed. In the variable speed transmission, this might also result in oil

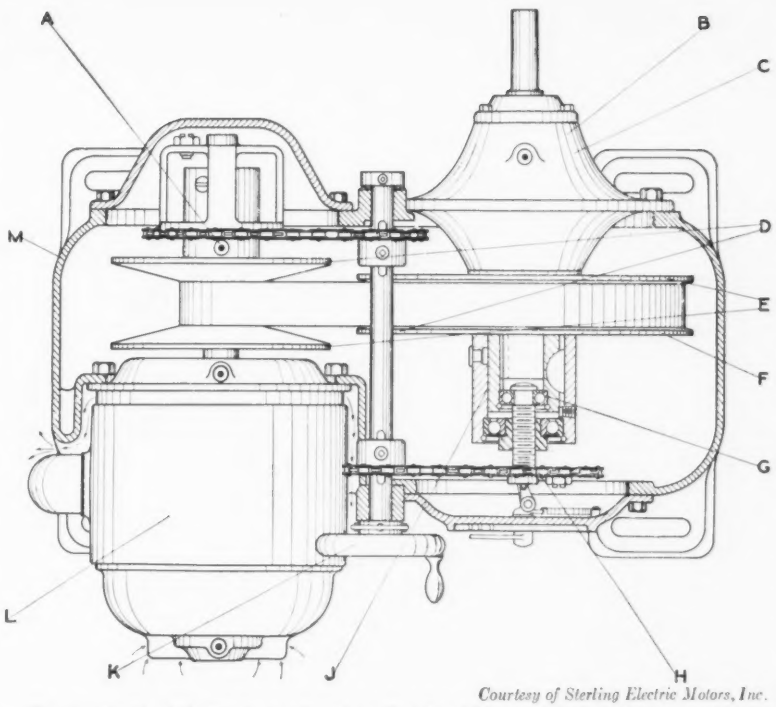


Courtesy of Link-Belt Company

Fig. 10—The Link-Belt P.I.V. Gear with cover raised showing compactness of design, and safety, due to all parts being fully housed. The design of this mechanism allows for lubrication of all parts with a high grade straight mineral lubricating oil, which will possess adequate fluidity at the operating temperature to enable operation with minimum power consumption and afford positive protection of all wearing elements.

dripping or being thrown on to the V-belt to impair the fabric and reduce the traction effect on the pulleys.

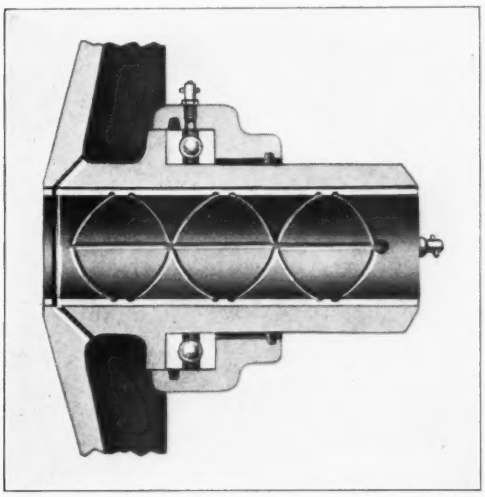
Where bearings of this nature are exposed so that operators may safely feel of them, the conclusion may often be drawn that increase in temperature is due to lack of lubrication. On the other hand, where a bearing runs warm due to too heavy a grease, addition of more of this latter will only aggravate conditions. There will also be the danger of forcing some grease past the seals. For this reason, operators should be carefully educated in regard to the lubricating requirements of ball and roller bearings, just as the management should be impressed with the folly of purchasing unsuitable products, often on a price basis. It is especially necessary for the operator to remember that bearings of this type have but a limited capacity for grease, which should never be exceeded.



Courtesy of Sterling Electric Motors, Inc.

Fig. 11—Details of the Sterling enclosed type Vari-Speed Motor. This installation gives infinite speed variation. (A) indicates high pressure lubrication fitting for pulleys and bearings; (B) Sterling standard Slo-Speed and Hi-Speed gear unit; (C) shows rigid shaft sub-assembly with heavy wide-spaced ball bearings to insure permanent alignment; (D) indicates the moveable pulley faces; (E) fixed halves of these pulleys keyed to the shafts. Speed variation is obtained by moving one side as (F) to change the belt operating diameters; (G) is a radial thrust ball bearing; (H) indicates a heat treated sprocket chain; (J) shows rust proof metal sliding surfaces used in both pulleys; these are pressure lubricated; (K) the hand wheel for change of speed operation; (L) indicates driving motor, and (M) the housing which protects the belt and operating mechanism.

Unfortunately, there is no direct method by which application of grease to anti-friction bearings can be controlled. Certain types of bearings, however, can be vented to reduce the possibility of imposing the full pressure of the lubricating equipment upon the seals; these latter must of course be maintained in suitable condition with respect to the housing if they are to positively prevent leakage of lubricant under continuous operation.

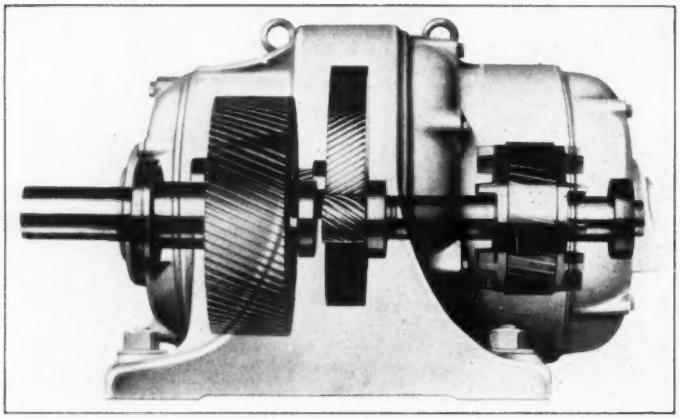


Courtesy of Reeves Pulley Company

Fig. 12—Sectional view of the Reeves Disc and Thrust Bearing, showing provision for distribution of lubricant and means of application. It is highly essential that the grease used in these bearings be capable of resisting separation or oxidation. It should not be too heavy a product otherwise it may resist complete distribution. A low torque grease is highly advantageous in the interests of reduced power consumption.

Selection of the Lubricant

Authorities are agreed that grease for ball or roller bearing lubrication must be practically free from acid-forming tendencies if positive protection of the highly polished metallic surfaces is to be maintained. This necessitates a virtually neutral product and one which contains no fillers. The grease must also show minimum tendency towards oxidation, decomposition, separation and development of free acidity, otherwise corrosion or pitting of the surfaces of the rolling elements may result. For bearing lubrication in electric motor or variable speed transmission service, a grease compounded from a medium viscosity, highly refined, straight mineral oil and a soap which is suitable to comparatively high temperature service will give lowest starting and operating torque and best assurance against separation and oxidation.



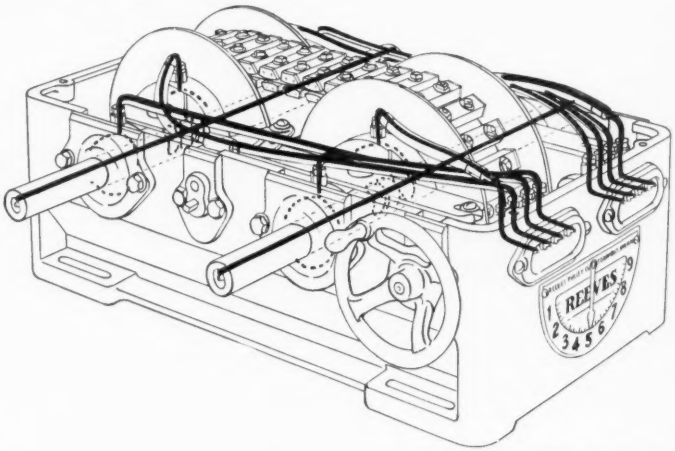
Courtesy of U. S. Electrical Mfg. Co.

Fig. 13—Phantom view of U. S. Synchrogear installation, wherein bearings are provided for grease lubrication, the gears being oil lubricated. Where the larger gear is below the pinion the gears dip into the oil. Where the larger gear is above the pinion, a slinger is provided which throws oil over both the gears and bearing.

overhauling the unit with costly replacement of wheel bearings, chain links and other parts. The extent to which the ball bearing has been adopted renders thoughtful study of lubrication all the more important, for use of unsuitable greases which may tend to oxidize will seriously impair the free motion of the rolling elements and lead to abrasion or even sticking of the bearings. The use of very finely designed chain mechanisms in the flexible chain transmission, in turn, calls for use of a most carefully refined oil and study of viscosity with due regard to the operating temperatures. The progressive operator fully realizes that this will insure against premature breakdown and the possibility of serious damage.

CONCLUSION

The foregoing discussion of the mechanical type of variable speed transmission has been presented for the purpose of emphasizing the fact that lubrication is one of the salient features involved in the successful and economical transmission of power with the minimum cost of maintenance. Too often has the impression been gained in the operation of such devices that lubrication is relatively unimportant, due to the fact that they will operate with apparent success under most severe conditions. Unless lubrication is maintained, however, with oil or grease adapted to the design, and capable of resisting oxidation and sludge formation, wear may be developing unknown to the operator. Ultimately this wear will necessitate



Courtesy of Reeves Pulley Company

Fig. 14—Showing the lubricating system of the Reeves Variable Speed Transmission. Heavy black lines indicate means of lubricant transmission from point of application outside of the case. All operating parts are mounted on ball bearings which are kept supplied with fresh, clean lubricant at all times. Centralized lubrication of this nature is an assurance against entry of dust and imperfect functioning of the mechanism.

Thin Oil Film Lubrication

So far, in this series of articles we have considered the question of what happens at the contact faces of metals rubbing together with a very thin film of lubricant between them. We have seen that when the film is about 10 molecules thick, we are in the boundary region, where the laws of ordinary fluid lubrication no longer apply. On passing from the fluid film to the boundary film region, the frictional resistance to motion increases abruptly to a relatively high value, and at the same time a new effect is introduced, corresponding somewhat to the yield point in plastic flow. If an attempt be made to slide one metal surface over the other, it is necessary to apply a definite force before it will move at all, whereas if the oil film is thick enough to be described as a fluid film, the slightest applied force will cause relative movement.

The question we are now to consider is—what happens at surfaces in contact when there is absolutely no oil film present between them.

WHAT IS A CLEAN SURFACE?

Absolute cleanliness is an ideal to aim at, but an extremely difficult one to realize. It means in effect the complete absence of any foreign material whatsoever, and is a term reserved almost exclusively to describe the condition of the surface of a body, rather than its volume purity. For instance, it is possible to distill water to a high state of purity, but quite difficult to maintain a clean surface on water exposed to the ordinary atmosphere of a room. After a short time, a film of greasy matter will form on the water surface, forming an adsorbed layer, possibly only a molecule thick, but quite sufficient to modify very radically the physical state of the free surface.

An oxidized metal such as iron is extremely difficult to clean, since in an ordinary atmosphere containing water vapor and oxygen, a film of oxide will form on the oil-free surface almost instantaneously. If it were possible to produce a clean surface on iron, it could be easily wet by mercury. It is stated in the literature that if a rod of steel be broken beneath the surface of pure mercury, the fractured surfaces become amalgamated, proving the state of absolute cleanliness of the newly exposed metal surfaces.

In general, the water wetting test is a useful and simple way of proving whether a surface is free from oil. If a surface, say of glass or steel, carries a film of oil even as thin as one molecule, and is then flooded with water, and shaken, the water will run off, leaving the surface apparently dry. But if an adherent film of water remains, it proves that the surface is relatively free from oil or grease.

An exceedingly interesting experiment can be performed which shows very strikingly the effect of entire absence of any contaminant on a glass surface. A sheet of plate glass and a glass slider in the form of a low tripod are required. Both are made absolutely clean, and the most efficient method of doing this is by the use of a mixture of concentrated nitric acid, and alcohol. A very violent reaction starts a few seconds after these materials are mixed, and nitric peroxide is formed in great quantity. Complete oxidation of oil and organic matter present on the surfaces takes place, and after thorough washing with water and natural drying by evaporation, the glass plate and slider are clean in the absolute sense of the term. This can be proved by the tilting test. The slider is picked up by forceps, care being taken not to allow the working surfaces of the tripod legs to touch anything whatsoever except the clean surface of the glass plate on which the slider is placed. The plate is then tilted

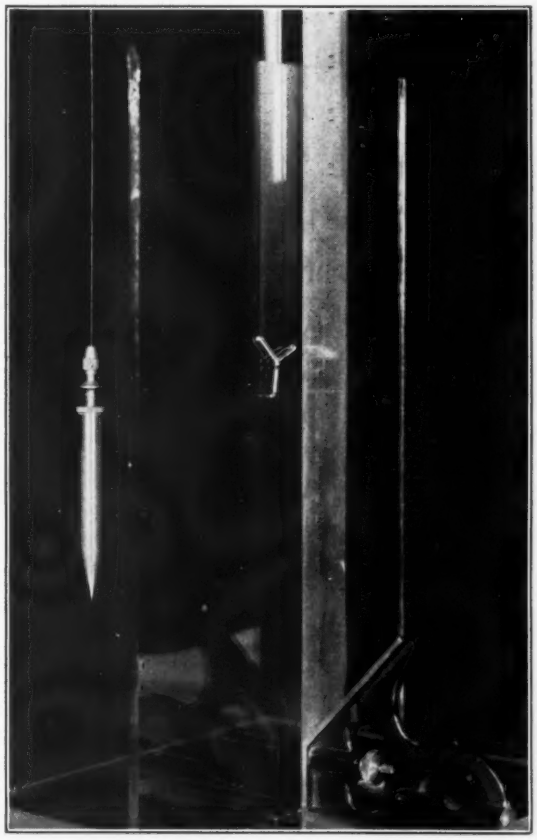


Fig. 1—Showing effect of absolute cleanliness. Glass slider adhering to vertical glass surface.

about one edge, and it will be found possible to raise it to a vertical position as is illustrated in Fig. 1, without any slip taking place.

Since the angle of tilt is now 90 degrees, the coefficient of static friction is infinite, which means in effect that the slider feet are adhering to the plate surface, since pressure due to the weight of the slider is obviously zero. Irving Langmuir in 1922 described this experiment, reaching an angle of tilt of 90 degrees before the slider slipped. He used for his cleaning agent either fuming sulfuric acid, or a mixture of sulfuric and chromic acid. It happens, however, that the mixture of concentrated nitric acid and alcohol used in the experiment here described is more efficient, as it has been found possible to tilt the plate beyond 90 degrees as is shown in Fig. 2. There is obviously very complete adhesion between the glass surfaces in contact, and to show that the force of adhesion exceeds the weight of the slider, the plate was turned upside down, without causing the slider to fall. Fig. 3 shows this remarkable result, the beaker of water standing on the plate being used to orientate the set-up.

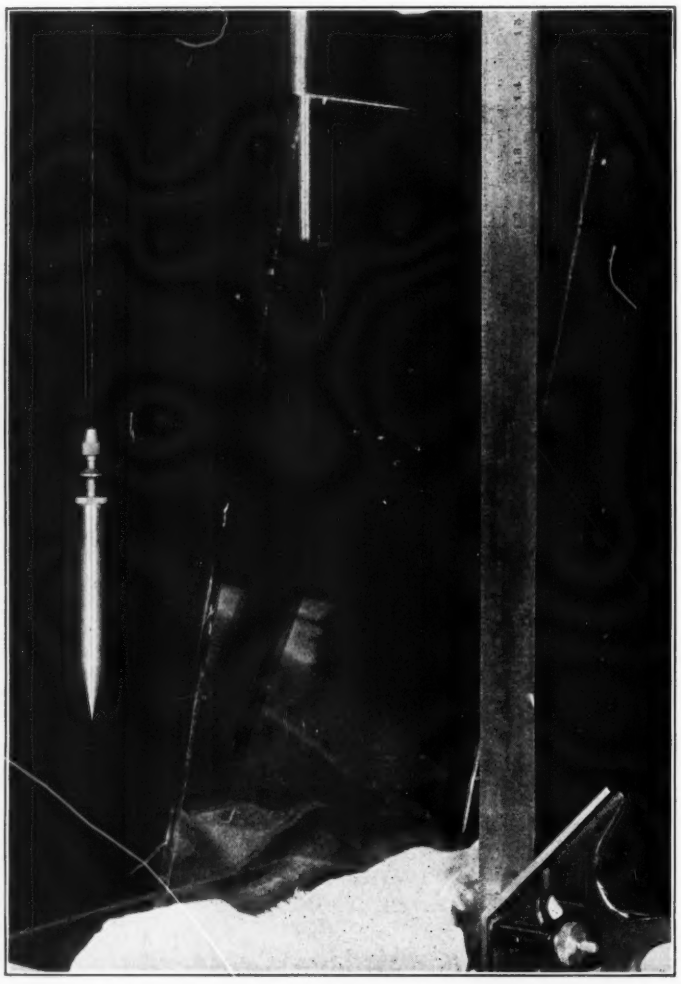


Fig. 2—Glass plate about 15 degrees over vertical, with slider still adhering to surface.

The explanation for what is happening is found in a consideration of the field of force existing at the contact surfaces. In the total absence of a third material as contaminant, the glass surfaces are so close as to come within the zone of their mutual fields of force. It is known that the intensity of this field falls off very rapidly away from the surface, and it is probable that in the case described, the molecular boundaries of the surfaces of the slider contact points, and of the plate on which they rest, are practically identical.

CAUSE OF ABRASION OF BEARING SURFACES

If two solid bodies, say two pieces of steel, are placed in contact, one can be moved over the other without damage, only if they do not touch. If the two surfaces are clean, they will touch, and any relative motion will damage the surface, or will cause seizure. Fig. 4 is a photomicrograph to 25 diameters of what happened to the surface of a piece of clean steel piano wire when it was lightly rubbed with a similar piece of clean wire. The abraded spot seen across the middle of the wire, which looks as if it had been produced by a file, is exactly typical of every case of breakdown of lubrication.

So long as there remains even the very thinnest oil film on the surfaces of rubbing metals, the only wear possible is polish wear, which means the slow, smooth removal of surface molecules of metal, resulting in the high burnish greatly to be desired in bearings.

If, however, this ultimate protecting oil film is removed, the situation is radically changed. When two perfectly clean metals are rubbed together they seize, and metal is violently dragged deep out of the contacting surfaces. This removed metal consists of enormous aggregates of molecules, and the process is in striking contrast to the smooth flow of surface molecules which takes place in polish wear.

Observation shows that it is from the softer of two rubbing surfaces that metal is removed, and a considerable proportion of this is welded to the harder surface, forming what is virtually a collection of cutting tools, which still further damages the other surface. The damage done by seizure is complete and irreparable, and it is obvious that the problem of means to avoid breakdown of lubrication is one of the first importance.

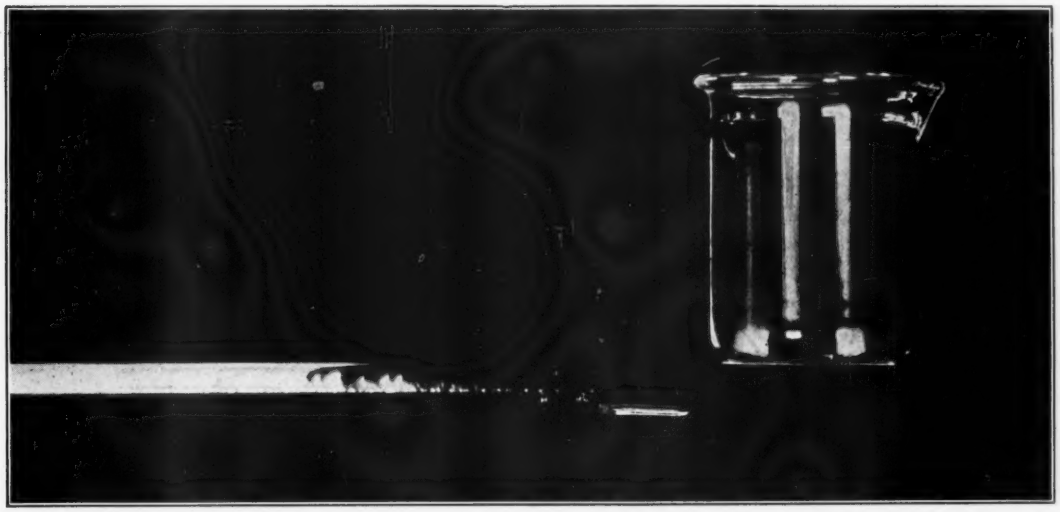


Fig. 3—Slider adhering to under-side of glass plate. Force of adhesion is greater than the weight of the slider.

WHY DOES AN OIL BREAK DOWN?

We have seen that the normal state of a surface is one of contamination, and that it is difficult both to clean it, and to keep it clean. Further, that such contaminated surfaces when brought into contact do not actually touch. The only way of making them actually touch is to remove the contaminating films. It is rather interesting to note that it is impossible to remove the last trace of oil from a metal surface by means of solvents. Suppose we flood the surface of a piece of polished steel with oil, and then wash it in several changes of carbon tetrachloride, or benzene, or acetone. To all outward appearances, all the oil will be removed by the solvent, but the water wetting test will show that a strongly adherent film still remains on the surface.

This adsorbed film, which resists perfectly the action of a solvent, is easily removed, however, by a simple polishing process. If the steel surface is rubbed with a mixture of chromic oxide and water, followed by a treatment with the dry powder, no trace of oil will remain, as can be proved by the water wetting test, or by rubbing the cleaned metals together, in which case deep scoring will result.

Returning now to our original question as to the cause of mechanical breakdown of an oil film it will be easily seen that the mechanical work of friction at the rubbing surfaces provides an entirely reasonable explanation. The adsorbed oil film is continually being removed, and replaced just as rapidly as it is removed, by virtue of the forces of attraction between the free surface of the metal and the oil molecules. So long as the friction is not excessive, the rate of removal of the film does not exceed its rate of renewal, but if either the load or the speed is increased to a point where the work of friction reaches a critical value, clean metal contact occurs, with resulting abrasion.

RELATION OF FILM BREAKDOWN TO SURFACE FINISH

This is rather an academic question, since oftentimes all that can be done is to delay the inevitable breakdown when the destructive agencies become too severe.

If we examine the problem more closely and inquire what practical means are available for decreasing the risk of breakdown, we find that it is a problem involving both the oil and the perfection of finish of the metal surfaces. The petroleum industry is prepared to furnish lubricants which will meet satisfactorily every class of service, but it is felt that the machinery industry has largely overlooked the great gain in safety and power saving which follows the use of properly run-in rubbing surfaces.

It has previously been pointed out that the most perfect surface which it is possible to produce is still very far from being geometrically true. It is covered with high spots or plateaus above the general level, and these constitute a

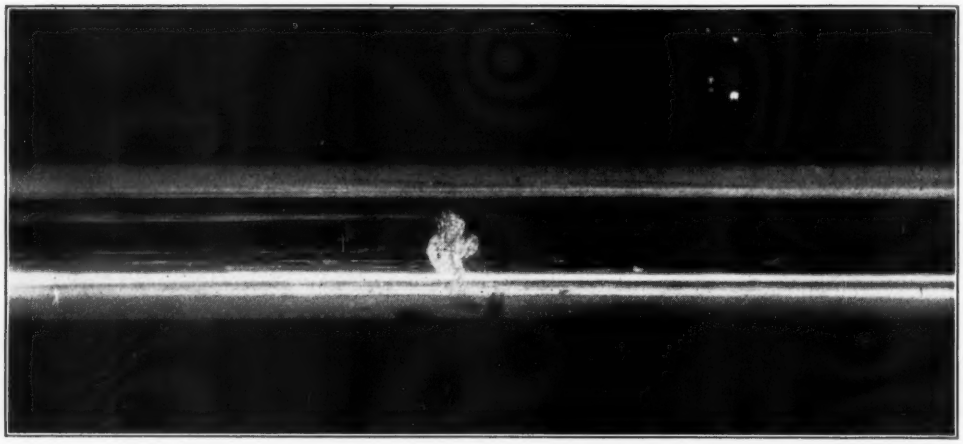


Fig. 4—Showing amount of abrasion produced by lightly rubbing one clean steel wire across another.

potential source of danger when the surfaces approach very closely.

One of the most difficult problems of lubrication which has developed in the last few years is in connection with hypoid gears. Intensity of load and speed of rubbing are both high, which means that the work dissipated in friction is also high. In other words, we have high power losses and we have wear. Polish wear is desirable, but abrasive wear should be avoided, and this constitutes the real problem. Under the high loading the oil film between the high spots becomes extremely thin. So long as it exists at all there can be no clean metal contact, and therefore no abrasion, but this state of affairs can only continue so long as the rate of removal of the film does not exceed its rate of renewal.

Extreme pressure lubricants have been advocated for use with hypoid gears, but their inherent disadvantages such as thickening, wear and corrosion have raised doubts in many quarters as to their desirability in regular service. This type of lubricant contains some chemically active body such as sulphur or chlorine, which will react with the metal when the temperature, due to the heat of friction, becomes high enough. There is thus produced on the rubbing surfaces a tough, resistant film of iron sulphide, or iron chloride, which is less easily removed than is a film of oil, and in consequence the margin of safety is considerably widened.

It must be strongly emphasized that the employment of an extreme pressure lubricant in regular service is an expedient made necessary by the condition of the metal surfaces. Were these surfaces extremely well burnished, there would be little or no need to consider the use of a doped lubricant. It is suggested that extreme pressure lubricants have their rightful place as very valuable materials for the pre-conditioning of metal surfaces. The very fact that high loads may be used with safety in the running-in operations means that in a comparatively short time high spots will be polished down, and the surfaces will acquire the extreme burnish so greatly to be desired, since it spells both safety and lowered power loss. The extreme pressure oil is then replaced by an undoped lubricant of a viscosity suited to the load which is to be carried.

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